Nonvolatile Rad-Hard Holographic Memory

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ABSTRACT

We are investigating a nonvolatile radiation-hardened (rad-hard) holographic memory technology. Recently, a compact holographic data storage (CHDS) breadboard utilizing an innovative Electro-optic scanner has been built and demonstrated for high-speed holographic data storage and retrieval. The successful integration of this holographic memory breadboard has paved the way for follow-on radiation resistance test of the photorefractive (PR) crystal, Fe:$LiNbO_3$. We have also started the investigation of using 2-photon PR crystals that are doubly doped with atoms of iron group (Ti, Cr, Mn, Cu) and of rare-earth group (Nd, Tb) for nonvolatile holographic recordings.

I. INTRODUCTION

NASA's future missions would require massive high-speed onboard data storage capability [1]. This is a particularly challenging technology issue for long-life, deep space missions. The memory technology required to support these missions have to be rad-hard and nonvolatile (i.e. no loss of stored data after power switched off). Nonvolatile memory is critical to spacecraft's ability to survive fault conditions (i.e. no loss in stored science data when spacecraft enters the "safe mode") and autonomously recover from them. In addition, this nonvolatile memory has to be rad-hard to survive the stringent space environment (e.g. very high radiation around Europa where radiation exceeding 1 Mrad). It should also operate effectively and efficiently for a very long time (10 years), and sustain at least a billion (10^{12}) write cycles.

Current technology, as driven by the personal computer and commercial electronics market, is focusing on the development of various incarnations of Static Random Access Memory (SRAM), Dynamic Random Access Memory (DRAM), and Flash memories [2, 3]. Both DRAM and SRAM are *volatile*. The Flash memory, being nonvolatile, is rapidly gaining popularity. Densities of flash memory of 512 Mbits per die exist today. However, Flash memory is presently faced with two insurmountable limitations: 1) poor radiation-resistance (due to simplification in power circuitry for ultra-high density package); and 2) Limited endurance (breakdown after repeated read/write cycles).

JPL, under sponsorship from NASA Earth Science Technology Office, is currently developing a high-density, nonvolatile and rad-hard Compact Holographic Data Storage (CHDS) system to enable large-capacity, high-speed, low power consumption, and read/write of data for potential commercial and NASA space applications [4,5]. The CHDS stores data in the form of holograms inside a photorefractive (PR) crystal. In operation, pages of holograms would be recorded and retrieved with random access and high-speed. Since these holographically recorded images are stored in three dimensions and uniformly spread out throughout the entire recording volume, massive redundancy is built into the holograms, and the stored data would not suffer from imperfections in the media or point defects. This massive redundancy forms the basis for radiation-resistance. On the other hand, recent advances in new photorefractive material research make it possible to extend the lifetime of the holograms recorded in PR crystals from months to decades or longer [6]. The nonvolatile, rad-hard characteristics of the holographic memory will provide a revolutionary memory technology to enhance the data storage capability for all NASA's Earth Science Missions.

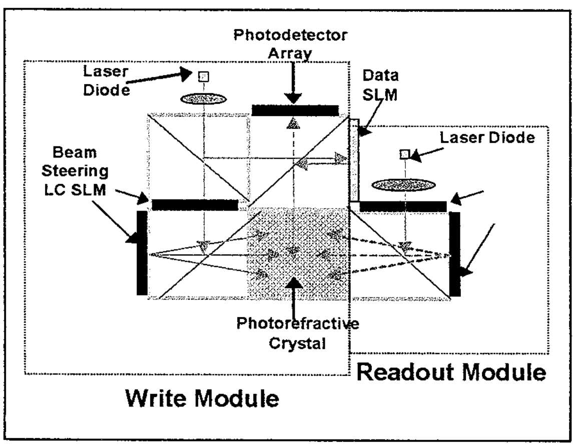
In this paper, we will first briefly report the most recent progress in developing this CHDS at JPL. Ongoing and future research effort in developing nonvolatile rad-had photorefractive recording materials will then be discussed in detail.

II. CHDS BREADBOARD DEVELOPMENT AND EXPERIMENTAL DEMONSTRATION

JPL has recently built a fully functional book-size CHDS breadboard using liquid crystal SLM as beam steering device [4,5]. Figure 1a shows the CHDS architecture, and Fig.1b is a photograph of the CHDS breadboard. In this breadboard we have implemented a 1-D scanning scheme using a single beam steering SLM (from Boulder Nonlinear System, Inc.) which is capable of recording 128 resolvable holograms to date. A LabView based system controller has been developed to perform holographic data recording/retrieval in an autonomous manner.

We have successfully performed hologram recording/retrieval demonstrations using this breadboard. During this experiment, we have utilized a sequence of grayscale images of the near earth asteroid, Toutatis, as the input. A few retrieved images from the holograms recorded in the $LiNbO_3$, presenting the Toutatis viewed in several aspect angles, are shown in Figure 2.

In the next step, a pair of this BSSLM will be cascaded to enable 2-D scanning of the reference beam to increase the number of stored holograms. This 2-D beam multiplexing would result in a total of 11,520 resolvable scanning angles. Thus it will enable the storage of more than 11,000 pages of holographic data within a 1-cm^3 volume of a PR crystal. The total storage capacity, when using a 1000x1000 pixel size SLM as input device, would exceed 10 Gbs. Further increase the input frame size (e.g. 5000x5000 pixels) would further increase the memory size to 250 Gbs.



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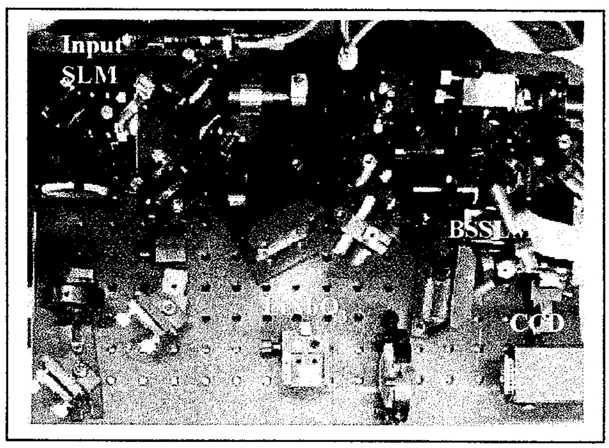


b

Figure 1a. System schematic architecture of an Advanced Holographic Memory
1b. A book-sized CHDS breadboard under development at JPL

The potential of stacking a multiple of very compact holographic memory cubes on a memory card (e.g. 10 x 10 cubes on each card) will provide up to 1 terabits storage capacity per card. The transfer rate ranges from 200 Gbs/sec (with nematic liquid crystal BSSLM) to 2000 Sec/sec (with ferroelectric liquid crystal BSSSLM). In summary, primary advantages of this holographic memory system include: high storage density, high transfer rate via randomly accessible E-O beam steering, compact and ruggedness, low voltage and low power consumption.

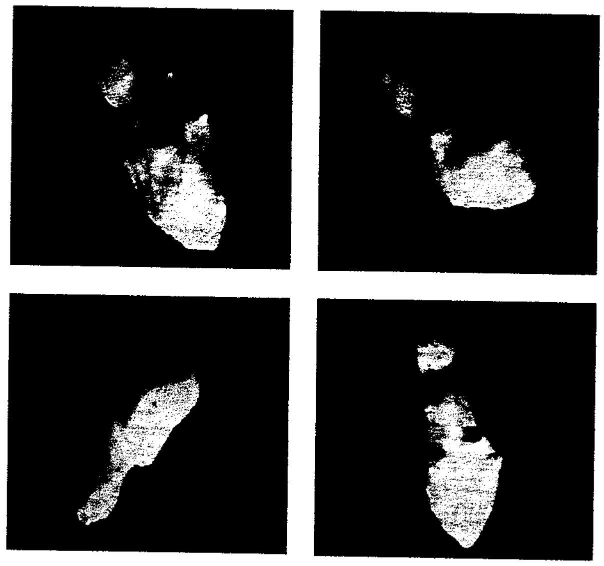
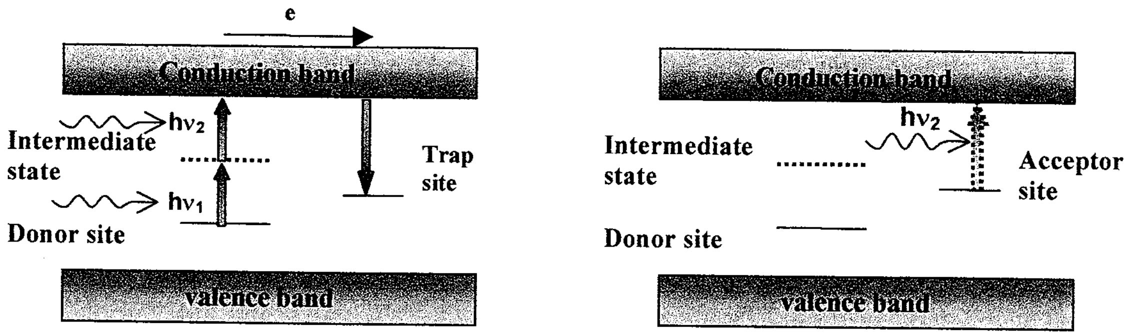


Figure 2 Experimental results showing retrieved holographic images of asteroid Toutatis.

III. NONVOLATILE PHOTOREFRACTIVE MATERIAL

Recently, technology breakthrough in extending storage lifetime of photorefractive memory from months to decades or longer have been reported by researchers at Caltech and elsewhere. A new type of two-photon recording material, doubly doped $Fe:Mn:LiNbO_3$, has been developed. This material possesses a deep traps partially filled with electronics and a shallow (intermediate) traps to trap photo-generated electrons with very long lifetime. Doubly doped extrinsic dopants (Fe^{+2}, Mn^{+2}) would provide this intermediate state. As illustrated in Figure 3: During recording, a first photon (from an ultraviolet light source) is used to excite an electron form the Valence band to an intermediate state. A hologram writing photon is then used to bring the electron up to the Conduction band. The electron will then migrate and get trapped to record the interference pattern. During readout, the readout beam will readout the hologram but is with insufficient energy to elevate the electron to the conduction band. Hence the stored hologram will not be erased during readout.

More recently, more doping ions from the iron group ions (Ti, Cr, Mn, Cu) [6] and the rare-earth group ions (Nd, Tb) [7] have been investigated for nonvolatile performance in a $LiNbO_3$ crystal. To date, it has been reported that doubly doped $Cr:Cu:LiNbO_3$ as well as Fe: $Tb:LiNbO_3$ are effective in nonvolatile holographic recordings.



a. Recording b. Readout

Figure 3. Two-photon nonvolatile hologram a) recording and b) reado

We have recently started the investigation of the holographic performance of new two-photon PR $LiNbO_3$. We are in the process of acquiring $LiNbO_3$ crystals doped with various 2-photon dopants and concentration (e.g., Fe:Mn: $LiNbO_3$, Cr:Cu: $LiNbO_3$, Fe:Tb:$LiNbO_3$, and Ce:Mn: $LiNbO_3$). Once acquired we will insert them into a holographic memory testbed for nonvolatile data storage performance evaluation. The holographic memory testbed under assembling for testing the nonvolatile data storage capability of candidate 2-photon PR crystals is shown in Figure 4. An iterative test procedure will be developed during the test of the doubly doped $LiNbO_3$ PR crystal. The dopant type and concentration of the PR crystal will be altered for maximum nonvolatile memory performance. The selected PR crystal will then go through radiation tests until the optimum combination is identified.

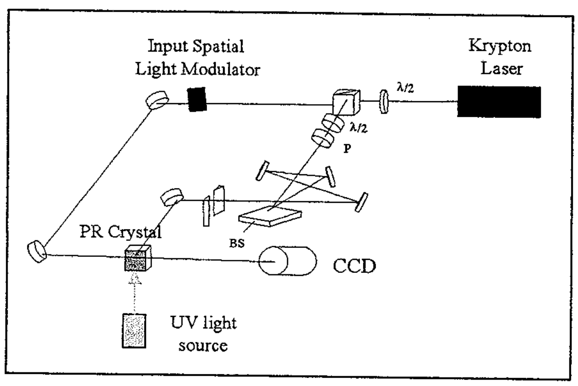


Figure 4. Experimental set up for holographic recording using 2-photon PR crystal (Krypton laser for holographic recording and readout, UV light source for flood gating)

IV. EVALUATION OF RAD-HARDNESS OF PHOTOREFRACTIVE CRYSTAL

The radiation environment in space depends strongly on location, and is composed of a variety of particles with widely varying energies and states of ionization [8-11]. The major types of radiation that are potentially hazardous to memory systems (electronic and holographic) include high-energy photons (X-ray, gammas), neutrons, and charged particles (electrons, protons, alpha particles, heavy ions). The parameters, which determine the amount of damage introduced by a particle, are the rest mass (e.g. zero for protons), the energy and the charge state (e.g. electronics are negative, protons and alphas are positive. Ions can even be multiply charged).

The radiation in space has a degrading effect on the microelectronic devices. For example, neutrons bombardments of Si atoms will convert them into Phosphorous (Neutron Transmutation Effect) that will adversely affected the performance of electronics. The radiation effect on the $LiNbO_3$, the most important PR material, has been partially investigated in literature. In general the degrading effect of radiation on Lithium Niobate is a function of the type of the dopants and of the radiation dose [8-11].

The primary radiation effects on PR crystals due to all types of aforementioned radiation sources include variations in refraction index, spectral absorption (coloring), and change of density (volume expansion and striation). A summary of the previous study of the radiation effects on the doped $LiNbO_3$ is shown in Table II.

Table I. Radiation types and their damages to doped $LiNbO_3$ holographic material

Types of damages / **Source of Radiation**	Refractive index (Δn_o) changes	Density changes	Spectral absorption
X-rays, γ-rays	$\Delta(n_o)$ increases with dose	None	Spectral absorption in blue spectral region observed
Neutrons/charged particles	Decrease with dose	Volume increases at very high nuclear deposited energy	None

The preliminary results of radiation test of doped $LiNbO_3$ crystal have shown encouraging results that those damages occurred in orders of magnitude higher dose than that of the electronics. These tests indicated that rad-hard holographic memory could be developed using iron(s) doped $LiNbO_3$ PR crystal.

We will conduct a comprehensive radiation test of several doubly doped $LiNbO_3$ PR crystals. Specifically, we will measure the following key PR material parameters before and after the radiation tests: photorefractive sensitivity, recording time-constant, and material dynamic range (or maximum refractive index change). In addition, other material properties, such as optical uniformity, scattering noise, etc. would also be measured to evaluate the quality of the retrieved holographic data.

CONCLUSION

In summary, we have built a fully functional book-size CHDS breadboard using liquid crystal SLM as beam steering device and demonstrated the recording and retrieval of holograms with high quality. Radiation resistance test of the PR crystal LiNbO3 is under way. In addition, we have also started the investigation of new 2-photon PR crystals for nonvolatile holographic recording.

ACKNOWLEDGMENT

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